MODEL PREDICTIONS AND VISUALIZATION OF THE PARTICLE FLUX ON THE SURFACE OF MARS

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Running Title: **MODEL PREDICTIONS: PARTICLE FLUX ON MARS**

Keywords: **Mars / Radiation / Visualization / Particle Flux / GCR**

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ABSTRACT

Model calculations of the particle flux on the surface of Mars due to the Galactic Cosmic Rays (GCR) can provide guidance on radiobiological research and shielding design studies in support of Mars exploration science objectives. Particle flux calculations for protons, helium ions, and heavy ions are reported for solar minimum and solar maximum conditions. These flux calculations include a description of the altitude variations on the Martian surface using the data obtained by the Mars Global Surveyor (MGS) mission with its Mars Orbiter Laser Altimeter (MOLA) instrument. These particle flux calculations are then used to estimate the average particle hits per cell at various organ depths of a human body in a conceptual shelter vehicle. The estimated particle hits by protons for an average location at skin depth on the Martian surface are about 10 to 100 particle-hits/cell/year and the particle hits by heavy ions are estimated to be 0.001 to 0.01 particle-hits/cell/year.

INTRODUCTION

The human exploration of Mars is expected by most to occur in the first-half of the 21st century. In planning these missions, NASA and possibly other space agencies involved in these missions will place a high priority on the health and safety of astronauts[1]. A major area of concern is the possible detrimental health effects, including cancer, degenerative tissue diseases such as damage to the central nervous system and cataracts, and hereditary risks, caused by exposure to galactic cosmic rays (GCR) and solar particle events. The GCR contain highly ionizing heavy ions, which have large penetration power in shielding and tissue and are unlike any radiation to which humans are exposed on Earth. It is not possible to completely shield the GCR with practical amounts of radiation shielding because of their large ranges in materials and due to the production of secondary particles including neutrons as they penetrate materials [2]. In this report, we present model calculations and predictions of the particle flux of protons, alpha particles, and heavy ions on the Martian surface for solar minimum and maximum conditions. Because the uncertainties in defining the dose equivalent for the GCR are large [3], alternate quantities to discuss risks for exploration missions are needed. Here we consider one basic property, the number of particle traversals or hits per cell. We note that other quantities will be discussed elsewhere.

In our present model calculations we consider detailed calculations of the particle flux and organ dose equivalents on the surface of Mars with the inclusion of static CO_2 atmospheric shielding model based on the MOLA data [4]. Particle fluxes are presented in terms of the probable number of cell hits by protons, alpha particles, and distinct heavy ion charge groups ($3 \leq Z \leq 10$, $11 \leq Z \leq 20$, $21 \leq Z \leq 28$) in order to provide insights into the risks on the Mars surface from different GCR components. These calculations and model predictions are expected to provide guidance for radiation shield development and also influence the on-going radiobiology research investigations to assess future human missions to Mars.

METHODOLOGY

GCR Spectra

Using the HZETRN transport code, GCR spectra for several solar maximum and solar minimum scenarios was generated. Following Badhwar and O'Neill model [5)] the solar effects on the GCR are described in terms of the solar modulation parameter, Φ, with the results shown here for the current solar maximum (Φ = 1075 MV) (anticipated for the year, 2002) and near solar minimum (Φ = 428 MV)

Particle Flux

Making use of the HZETRN transport code [6)] and the QMSFRG nuclear interaction model [7)] the particle flux, $\phi_j(x,E)$, of ion, j with energy, E and depth, x is obtained from

$$\Omega\cdot\nabla\phi_j(x,\Omega,E)=\sum_k\int\sigma_{jk}(\Omega,\Omega',E,E')\phi_k(x,\Omega',E')dE'd\Omega'-\sigma_j(E)\phi_j(x,\Omega,E)$$

The methods of Wilson et al.,[6)] for GCR transport is to use the straight-ahead and continuous slowing down approximation to solve the above equation.

Dose Equivalent

Different types of radiation cause different amount of biological damage per unit of absorbed dose [8)]. Charged particles with higher rates of energy loss per unit length such as protons, alpha particles, and heavy ions are more effective in producing biological damage than particles such as electrons with lower rates of energy loss. One physical quantity used to quantify differences in the rate of energy loss per unit length of track in the material is referred to as the linear energy transfer (LET) and expressed as (keV/μm). Other approaches consider detail properties of the ion tracks [9]. It is well established experimentally that radiations with different qualities have different degrees of effectiveness in producing biological damage and the quality factor (Q) was introduced to weight the absorbed dose (D) in order to account for these differences [10]. The dose equivalent (H) is defined as the product of the quality factor (Q) by the absorbed dose averaged over a specific tissue (D_T) or integrated over the LET (L) distribution of a given radiation field, F(L) and expressed as Sieverts (Sv) [11].

$$H_T = D_T Q(L) = \int dL\, F(L)\, L\, Q(L)$$

There exists large uncertainties in Q (L); however, this approach is used here to illustrate our method of calculating risks at the Mars surface [11].

Martian CO_2 Model

For two different density models (16 and 22 g/cm^2), spherically distributed CO_2 atmosphere was considered [12]. The resultant shielding offered by the CO_2 atmosphere at a given altitude location is calculated for a set of 512 rays using the relation

$$s(z,\theta) = \sqrt{(R+h)^2 \cos^2(\theta) + \left[2R(z-h) + z^2 - h^2\right]} - (R+h)\cos(\theta)$$

Where, *h* is the altitude above the mean surface, *s* being the distance along the slant path with zenith angle, θ, (calculated between 0 and 90^0 with 10^0 increments) and *z* is the vertical height of the atmosphere above the identified location (Z_{max} = +8 km).

Visualization of the Radiation Environment

For the identified GCR environment, the particle flux as a function of altitude on the Martian surface was generated for protons, helium ions, and heavy ions binned into several charge groups. Utilizing the Martian topographical data from the MGS/MOLA mission [4)], Martian globes with the predicted radiation environment are generated to visualize the dose-equivalent values and particle flux. Visualization of the organ dose-equivalent values (cSv/yr), along with probable particle-hits by protons and heavy-ions (particle-hits/cell/yr) are presented at skin depth on the Mars surface. The dimension of the cell nucleus is considered to be 100 μm^2. Dose equivalent values include neutrons produced in the forward direction, but not the back-scattered *albedo* contribution. The *albedo* contribution is expected to increase the values here by about 10% with a larger contribution at low altitudes and a differential variation dependent on the local soil contribution of the surface [13)].

RESULTS AND DISCUSSION

Projections of particle-hits per cell on the Mars surface are estimated at organ depths in a human body behind a given conceptual vehicle with known water equivalent shielding in Table-1 near solar minimum and Table-2 near solar maximum. The differences between solar minimum and solar maximum on the Mars surface are reduced compared to Earth-to-Mars transit because the atmosphere of Mars shields the lower energy components that are highly modulated over the solar cycle. Visualization of the dose-equivalent values and particle-hits per cell on the Martian surface are presented in Figures 1 to 3 to show the range of variation across the entire surface of Mars. Visualization of the dose-equivalent values and particle-hits per cell in a human body on the Martian surface at mean altitude are presented in a separate report by Saganti et al., in this volume[13]. In this report, we have not included the contributions of the *albedo* neutrons produced in interactions with the Mars atmosphere or surface [14]. Such data indicate a correction needed to make a complete estimate of the exposures to be encountered on Mars. Quantifying the radiation risk uncertainty and mitigating the radiation risk on the Martian surface has been a priority for future manned missions to the Mars and for radiobiological investigations of the current era. These model calculations provide guidance for such investigations. These model calculations showed good correlation with the cruise-phase (April-August, 2001) and orbital phase (April 2002 – present) data of the Martian Radiation Environment Experiment (MARIE) instrument of the 2001 Mars Odyssey mission. These calculations and predictions on the surface of the

Mars are well correlated with the measurements obtained by the MARIE instrument and will be described elsewhere [15].

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Table-1: Model calculations of probable particle-hits per cell (100 μm^2) at average skin depth in one year near solar minimum (Φ = 428 MV). The altitude variation over the Martian surface (0 to + 8 km) provides < 10% advantage in the reduction of protons, and > 50% advantage in the reduction of all the ions (Z≥2).

	Particle Hits per cell per year (near solar minimum)				
Altitude (km)	Z=1	Z=2	3≥Z≤10	11≥Z≤20	21≥Z≤28
0	88.4	2.76	0.13	0.95×10^{-2}	1.32×10^{-3}
2	91.2	3.24	0.17	1.37×10^{-2}	2.07×10^{-3}
4	93.8	3.84	0.23	2.03×10^{-2}	3.34×10^{-3}
6	95.9	4.65	0.31	3.14×10^{-2}	5.68×10^{-3}
8	96.8	5.54	0.41	4.72×10^{-2}	9.44×10^{-3}

Table-2: Model calculations of probable particle-hits per cell (100 μm^2) at average skin depth in one year near solar maximum (Φ=1075 MV). The altitude variation over the Martian surface (0 to + 8 km) provides < 5% advantage in the reduction of protons, and ~ 50% advantage in the reduction of all the ions (Z≥2).

	Particle Hits per cell per year (near solar maximum)				
Altitude (km)	Z=1	Z=2	3≥Z≤10	11≥Z≤20	21≥Z≤28
0	42.7	1.46	0.08	0.67×10^{-2}	1.05×10^{-3}
2	43.3	1.71	0.10	0.94×10^{-2}	1.61×10^{-3}
4	43.8	2.01	0.13	1.35×10^{-2}	2.52×10^{-3}
6	43.8	2.40	0.17	1.99×10^{-2}	4.10×10^{-3}
8	44.2	2.82	0.22	2.87×10^{-2}	6.46×10^{-3}

FIGURE CAPTIONS

Fig. 1: Model predictions of the dose-equivalent (cSv/yr) from the GCR contribution as a function of the Martian topography. Calculations are shown at average skin depth near solar maximum (Φ = 1075 MV).

Fig. 2: Model predictions of proton flux (particle-hits/cell/yr) from the GCR contribution as a function of the Martian topography. Calculations are shown at average skin depth near solar maximum (Φ = 1075 MV).

Fig. 3: Model predictions of all ions ($Z \geq 2$ shown as particle-hits/cell/yr) from the GCR contribution as a function of the Martian topography. Calculations are shown at average skin depth near solar maximum (Φ = 1075 MV).

Fig. 1:

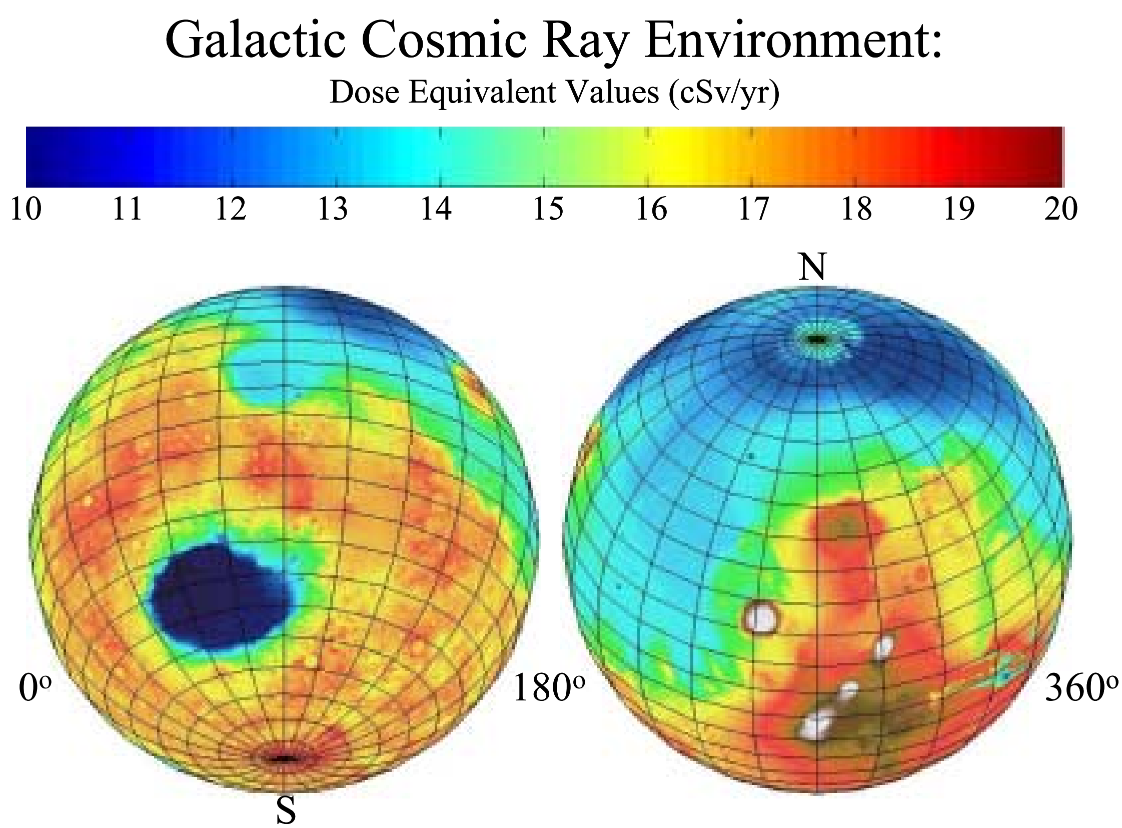
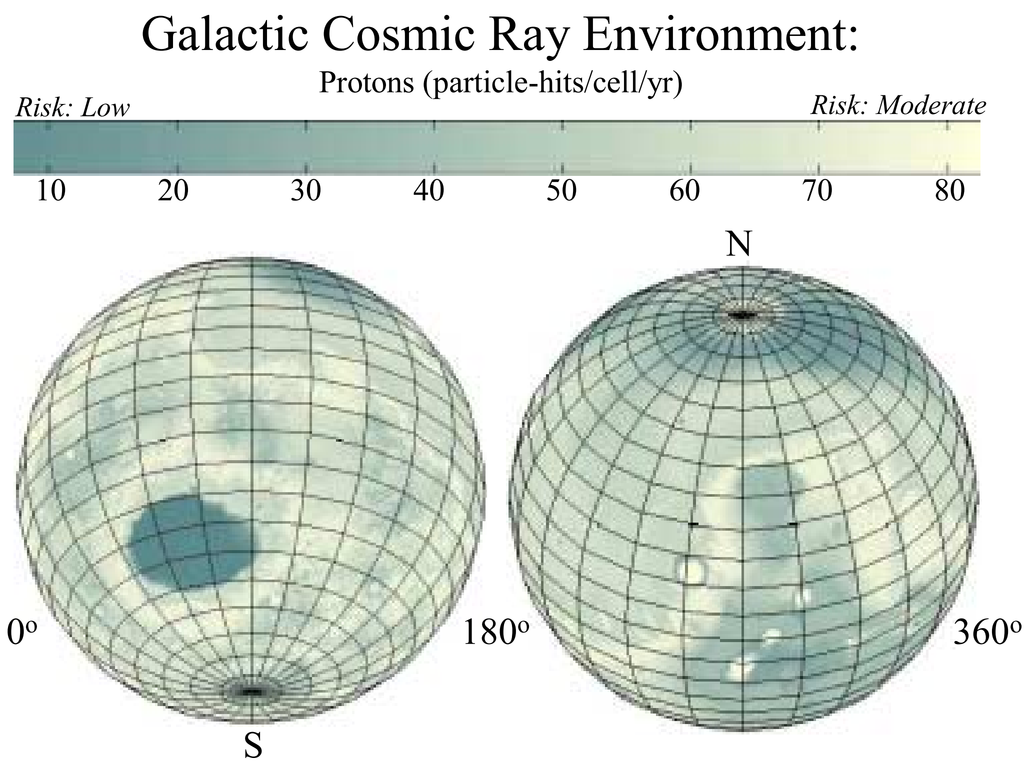
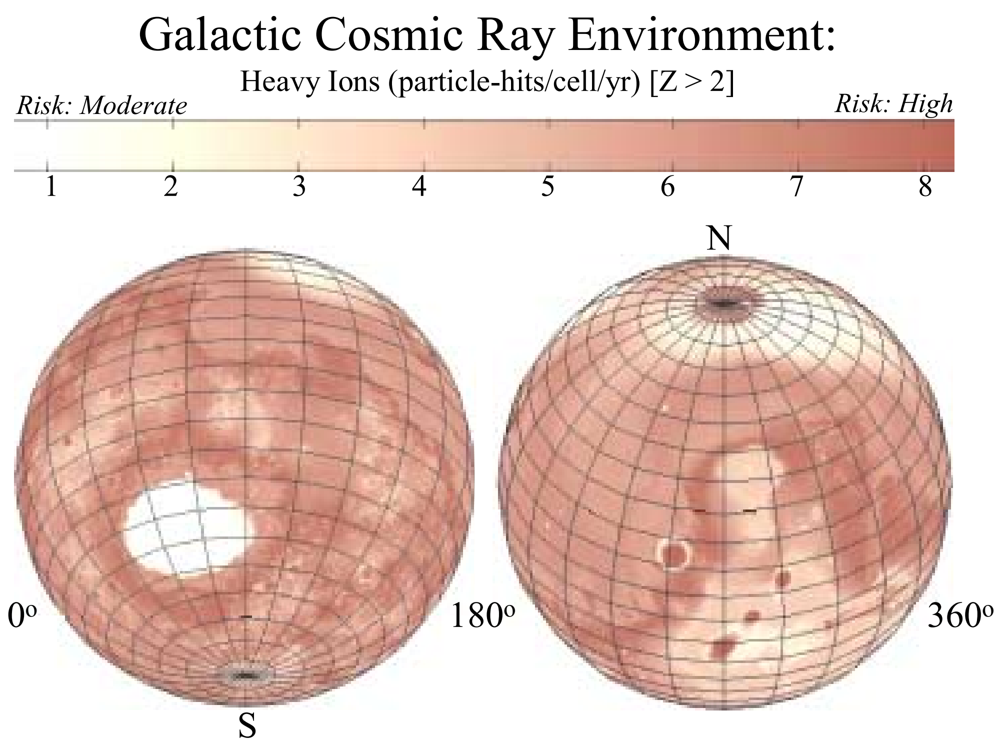

Galactic Cosmic Ray Environment:
Dose Equivalent Values (cSv/yr)
10 11 12 13 14 15 16 17 18 19 20
N
0°
180°
360°
S

Fig. 2:



Galactic Cosmic Ray Environment:
Protons (particle-hits/cell/yr)
Risk: Low
Risk: Moderate
10
20
30
40
50
60
70
80
N
S
0°
180°
360°

Fig. 3:



Galactic Cosmic Ray Environment:
Heavy Ions (particle-hits/cell/yr) [Z > 2]
Risk: Moderate
Risk: High
1
2
3
4
5
6
7
8
N
0°
180°
360°
S